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SUPERPLASTICITY OF METALS AND ALLOYS

by

Z. Misiolek, J. Turon

FOREIGN TECHNOLOGY DIVISION

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SUPERPLASTICITY OF METALS AND ALLOYS

Zbigniew Misiolek, Jerzy Turon

The state of world-wide investigations on the phenomenon of the superplasticity of metals and alloys is discussed. The essence of the phenomenon and the series of theories explaining its mechanism is described. At the same time, previous results are presented of tests for superplasticity utilization in technology as well as perspectives of its further development in the technology of conversion processes.

Introduction

Quickly developing technological advances include both new technologies and construction of machines and tools. The modernization of these latter is conditioned on the selection of materials with specific properties, speaking of which it should be stressed that, in spite of the recently great progress of the chemical sciences in the area of plastics and ceramics, metals and their alloys still continually play a fundamental role in the constructions discussed. However, we must take note of the significant progress and revitalization in investigations made within the scope of metallurgical processes and physical metallurgy in the search for new alloys having adequate mechanical and physical-chemical properties.

The result of this research is, among others, the testing of larger and larger numbers of alloys exhibiting the phenomenon of superplasticity,

characterized by exceptionally high plastic properties in a definite temperature range and speed of strain. Beyond the wide front of investigations as have been carried on in the Soviet Union (1-3) for the past 25 years in the field of metal superplasticity, interest in this area is also noted in the United States. The center for this research is found in the laboratory of Prof. Backofen at the Massachusetts Institute of Technology (4-9). In Europe research on the superplasticity phenomenon and the possibilities of its industrial utilization is conducted in Great Britain (10-12), Italy (13-15), and the Federal Republic of Germany (16, 17). In our country this type of research is conducted by Prof. T. Pelczynski of the Warsaw Polytechnic, and lately research on zinc-aluminum alloys and aluminum bronze of the type BA1032 was undertaken by the Institute of Nonferrous Metals.

The Phenomenon of Superplasticity

The concept of superplasticity defines the behavior of certain materials, which under the influence of applied stress, can display very great strain without breaking. This phenomenon is often observed by the heat method in the case of glass and polymers, but until recently it was rarely noted in the case of metals and alloys. These latter most often show strain within limits of 50-60% and in principle it does not exceed 100%, which size can be taken as the maximum limit to characterize the normal plasticity of commercial metals and alloys.

In alloys which, having appropriate structure and under definite conditions of temperature and speed of strain, exhibit the superplasticity phenomenon, the strain reaches a value of 1,000% (10), and can even approach 2,000% (11).

Figure 1 shows the differences in the straining of glass and plastics as well as metals having normal plastic properties and alloys exhibiting the phenomenon of superplasticity.

Saveur (18) was the first to uncover this phenomenon. In 1924, while conducting tests on iron bar twisting with a longitudinal thermal gradient, he proved that an entire twist of the bar takes place in the conversion range $a \rightarrow y$. He concluded from this that during conversion iron reaches a higher plasticity than that which can be obtained at lower and higher temperatures. In 1934 Pearson, testing the eutectic alloys Pb-Sn and Bi-Sn, got a strain within limits of 1,100% (19). However, it was not until 1945 that Boczwar (2), on the basis of investigations on Sn-Al alloys and extraction of similar results of an enlarged strain, proposed the term "superplasticity," which signified a strain increased many times within the range of uniform straining, and hence before the appearance of narrowing. This definition was again taken into consideration by Underwood in his research on the superplasticity phenomenon (7) and since that time has been universally accepted. Research

work treating the extensive investigations of the superplasticity phenomenon which was carried on after 1945 by Soviet researchers and particularly by Presniakov and his collaborators was the beginning of a vast amount of investigative research work and showed the wide possibilities of industrial utilization of the phenomenon. The following metal alloys were tested from the aspect of the appearance of the superplasticity phenomenon: Al-Zn (1, 2, 4, 17, 20, 21, 22, 23, 24), Al-Mg (25, 26), Al-Cu (1, 6, 26, 27), Al-Si (1), Cu-Mg (6), Cu-Zn (1), Cu-Ni (1), Pb-Sn (1, 6, 7, 8, 9, 15, 28), Ti-Al-Sn (1, 6, 8, 9, 29), Ti-Al-V (9), Bi-Sn (19, 30), Cd-Zn (31), Ni-Fe-Cr (32), Mg-Zn-Cr (33).

Presently, some scores of alloys and even metals are already known as, for example, titanium (6, 27) and uranium (34), which, under certain straining conditions, indicate the superplasticity phenomenon.

The current available literature on the subject of superplasticity of nonferrous metals and their alloys is very extensive. It will suffice to mention that a compendium of publications which appeared during the period 1958-1970 drawn up by the Metallurgical Institute of Czechoslovakia in Prague contains 228 items (35).

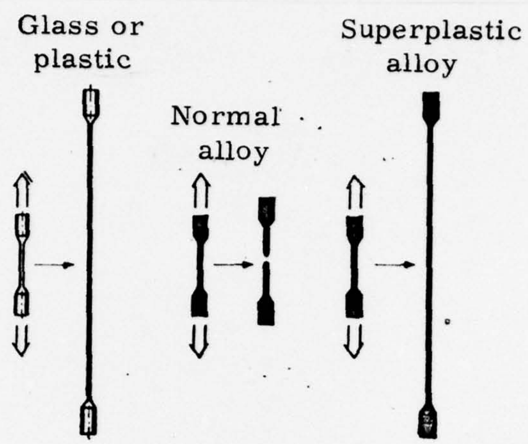

Fig. 1. Difference in the straining of glass, plastics and metals having normal plastic properties and alloys exhibiting the superplasticity phenomenon (Ref. 32 - p. 847)

One of the characteristic qualities of the superplasticity phenomenon is temperature, which is precisely fixed and most often amounts to nearly half of the fusion temperature measured on the Kelvin scale. Moreover, it has been proven that an alloy displaying the superplasticity phenomenon cooled down to lower than this temperature possesses normal physical, chemical, and mechanical properties, and, even the mechanical properties and corrosion resistance can be higher. For example, the so-called Lock-alloy (Be-Al), worked on by the English firm Lockhaed, is characterized by a 3-times greater tensile strength and 4-times greater elongation in relation to other alloys having the same chemical constitution (36).

Superplasticity appears, first of all, in those alloys having a eutectic or eutectoid composition, but is is not verified in alloys having a continual solubility of one component in another. Figure 2 illustrates this.

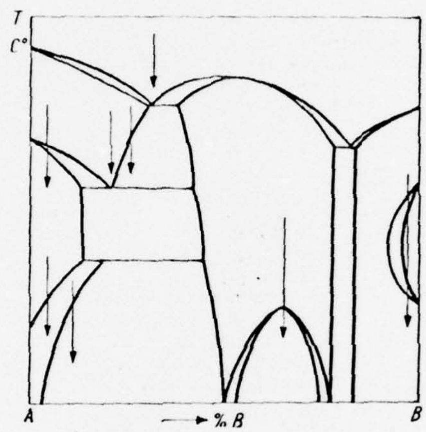

Fig. 2. Scheme of the constitutional diagram of binary alloys with clearly marked types of phase changes, which can accompany the effect of superplasticity. (Ref. 37 - p. 24)

Alloys displaying superplasticity have a characteristic, very fine-grained structure and, for example, if usually the size of the grain in alloys fluctuates within the limits of from 10 to 2,000 μ, then superplastic alloys have a grain the size of 1 to 5 μ. The microstructure of superplastic alloys contain 2 or more components, by which the fine grains of one of them are spaced among the grains of the other component. Such a structure is sometimes called "microduplex" and can be obtained along the way of various cuts of thermo-mechanical treatment. The presence of the second phase can

considerably limit the growth of the grain during heating of the alloy. It should be noted that the essential role in exposing the mechanism of superplasticity is credited to the phenomena occurring on the grain boundary (38). At the present time, it is generally accepted that superplasticity, like many other phenomena of plastic strains, is connected with a dislocation movement. The main difference relative to deformation of conventional metals depends on different conditions in the creation of the boundary, on which the dislocations come across, as the result of the fine-grained structure of the "microduplex" type (39). The characteristic features of superplasticity are: low tensile strength and very great strain. It must be remembered that metals straining at ambient temperature usually go through a hardening phase as the result of cold work during which the strain has two ranges--uniform and local extension, at which time a neck is formed, and then a break occurs. The universally known stress-strain diagram illustrates this. At the same time, it must be mentioned that according to Naziri and Pearce (40) superplastic alloys indicate exact dependence of stress during deformation on the speed of deformation, during which this stress does not depend on percentage elongation.

Metals usually accept in the whole range of plastic working within limits of 0.1 to 0.9 of fusion temperature Tm values of m lower than 0.2 and often even lower than 0.05. Hot method glass and some thermoplastic

materials have $m > 0.6$ and superplastic metals which have generally values of m in the range of 0.4-0.8 are distinguished by this same property (40). Another important agent which makes it possible to avoid the formation of a neck is the variability of the m value, which depends on the deformation speed. In the instance of common metals within the measure of deformation growth the value of m decreases insignificantly and uniformly, on the other hand, for the alloys indicating the phenomenon of superplasticity the maximum of the m curve appears depending on ε . For the purpose of creating conditions for the superplasticity to occur a temperature of near 0.4 Tm is required and the deformation speed contained in a definite interval, which position and range depend on the given material. At a speed lower than the lower limit of this interval, the normal creep phenomenon occurs, while higher, the material gradually nears retaining normal plasticity. Acceptance is indicated of the maximal value of the m factor, which according to Backofen and his collaborators (41) can be taken to characterize the capability of the material of plastic strain. Moreover, it can be considered an indicator of the sensitivity of the material to deformation speed.

Viewing the whole of the superplasticity phenomenon the mechanism as it operates during the plastic strain in these conditions is interesting. It should be mentioned that structural X-ray examinations of these metals before and after strain show their normal crystalline structure, in which very

fine grain 1-2μ in size before strain can rise to 4-5μ after strain. Thus, each superplastic alloy indicates a greater relationship of grain boundary surfaces to their volume than an alloy characterized by conventional plastic properties. It is a characteristic fact that in alloys exhibiting the superplasticity phenomenon a change in granular shape from globulitic to elongated is not observed. [36]

The ease of strain of a superplastic alloy is in principle a contradiction sought in many alloys, especially in heat-resisting ones, of creep strength. Since it is assumed that alloys with a coarse-grained structure show great creep strength, it seems that a fine-grained structure may be the key to superplasticity.

H. W. Hayden, R. C. Gibson and J. H. Brophy (39) suggested that in principle there exist 2 kinds of superplasticity. One of them is the so-called superplasticity arising from phase change, and thus one which has place at the time of allotropic changes in a definite temperature range. The other type of superplasticity is defined as the so-called isothermic superplasticity and this one--up to now-- is the subject of most of the investigations. It appears in the instance of operation of a definite load at a temperature equal to close to half of the absolute fusion temperature (^{o}K) of a metal or alloy respectively, or higher. Knowledge of the mechanism according to

which the superplastic strain runs has great significance, since it permits the evaluation of existing dependencies between parameters and their influence on the phenomenon under consideration in its various aspects.

The mechanism proposed by Boczwar (2, 3) assumes that superplastic strain is caused by an interaction of phases, which favors the passage of material from one phase to another as a result of the supersaturation-emission process.

Jong and Ratenau (42) advanced a theory according to which the low mechanical properties and high plastic properties of metal are connected with the change of unitary volume during the phase change and with tensile strength.

Clinard and Sherby's theory (43) explains superplasticity in steels given to a definite cycle of technological cuts, during which a considerably increased elongation is noticed for extracreep. According to Backofen and his collaborators (9) superplastic strain occurs through the viscose flow (slide) of certain grains in relation to others under the action of applied stresses. The slide will be facilitated and regulated by a process of damping and suppressing a "mechanical barrier," which is composed of irregular granular boundaries, stress concentrations at contact points of three

grains, and the like. These "mechanical barriers" can be suppressed or damped with the aid of three mechanisms: shearing at the granular boundaries, the slide according to Nabarro-Herring, and viscose creep through the granular network.

It is the theory of Backofen and his collaborators which, of all the theories known today, seems best to answer reality. It basically agrees not only with the results of microscopic observations and with the overall conditions of the appearance of superplasticity, but, moreover, it allows for the chief aspects of the phenomenon to be explained and can serve as a qualitative interpretation of it. The actual state of knowledge of superplasticity does not yet permit the formation of a general theory on the phenomenon. We can however, as a result of the discussion of the testing and investigations done so far and the theoretical considerations from the scope of the physics of metals, create a general and uniform image of the phenomenon from the various instances of its appearance. We must remember that various technological cuts necessary to achieve superplasticity in a definite alloy, and apparently differing from each other, in principle, give rise to the assurance of a very good and stable grain as well as definite temperature range and speed of strain.

Examples of the Appearance of Superplasticity in Several Metal Alloys

Zinc-aluminum alloys founded on this system were up to this time most often the object of interest of numerous researchers of the phenomenon of unusual plasticity of metals and alloys (1, 2, 4, 17, 20-24). They allowed many facts to be disclosed which approached explanation of the essence of the phenomenon, although none of the existing theories offered a conclusive mechanism. Presniakov (1) without a doubt was the earliest to describe the phenomenon of superplasticity in Zn-Al alloys in such a wide scope. He thoroughly examined the whole series of alloys containing from 5 to 95% Zn, in which he attempted to capture the effect of superplasticity by using systematic measures of elongation. Figure 3 presents the isothermal lines of plasticity of Zn-Al alloys obtained by Presniakov.

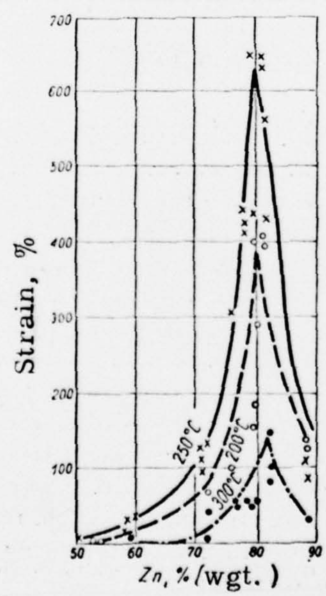

Fig. 3. Isotherms of Zn-Al alloy plasticity (Ref. 1 - p. 51)

Zn-Al alloys were also used in investigations on the superplasticity of metals by: Backofen and his collaborators(4), Chaudhari (44), Jovane (13, 14, 15), D.S. Field (22), Packer, Johnson, and Sherby (45). Although the results of the above investigations sometimes differ among themselves considerably, both by their results and the methodics of the investigations--in general, it can be summed up that in the Zn-Al alloys the superplasticity phenomenon appears most clearly when:

-- the test pieces undergo longer soaking at $> 275^{o}C$, and then a violent cooling,

-- the strain process is conducted in the temperature range of $250\text{-}275^{o}C$,

-- the time which lapsed from the moment of heat treatment to the deformation process is not too long (decomposition of frozen single-phase structure).

Aluminum-copper alloys (1, 6, 26, 27). Similar behavior of the eutectic alloy Al-Cu ($\sim$ 33% Cu wgt.) is established as in the case of superplastic Zn-Al eutectoid alloys. Here also the superplastic state appears after rapid cooling from a single-phase region to a diphase region. After homogenizing the phenomenon does not appear. A violent increase of plasticity is established at temperatures higher than $400^{o}C$.

B r a s s e s .   The phenomenon of superplasticity in brasses was investigated by Presniakov and his collaborators (1), who conducted tension tests at temperatures close to the phase change $\alpha \leftrightarrows \beta$. Maximal strains (~ 180%) were observed at 880°C (38% Zn wgt.) and 770°C (41% Zn wgt.). Figure 4 presents the strains obtained by tension of the above named alloys.

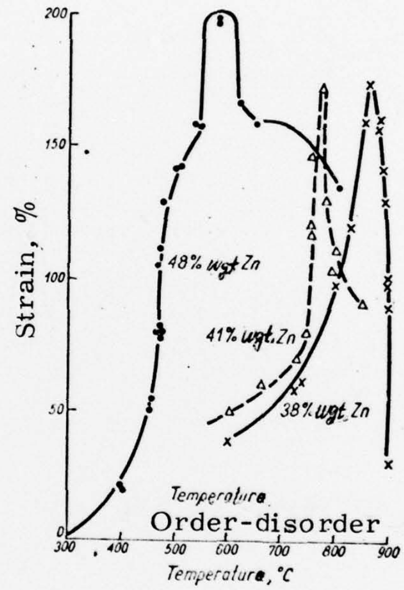

Fig. 4. Strain of Cu-Zn alloys near boundary of phase change and in a region of order-disorder (Ref. 1 - p. 101)

In the case of brasses Presniakov observed that similarly as in the case of the Zn-Al alloys, the greater the amount was of the metastable phase, the greater was the effect of superplasticity.

As can be seen from the list given in the second section of this article, the number of investigated alloys and nonferrous metals in which the appearance of the phenomenon of superplasticity was observed, is considerable and understandably we are restricting ourselves here solely to several examples representing a group of alloys most often used in technology.

The above examples deal with diphase alloys, however, as was mentioned earlier, the superplastic state was able to be secured in multiphase alloys as well as in fine metals.

Perspectives of Utilization of the Phenomenon of Superplasticity in Technology

The discovery and later, the rather detailed laboratory investigations of the phenomenon of superplasticity in metals and alloys gave rise to the vast and understandable interest in this problem, defined even as a "revolution" in metallurgy (36). From a theoretical point of view the essential, nontypical, almost Newtonian flow of metal during superplastic strain would indicate the just unlimited possibilities of the plastic working of metal semi-finished products, indicating superplastic properties and of securing elements which, up to now, could be produced entirely from plastic masses or glass, over which, after all, by reason of the superiority of their mechanical

properties, metals clearly prevail. Low resistance (Rm) and very considerable elongation in the scope of the existence of the superplastic state predestine new material to be used in almost all the traditional forming processes such as rolling, extrusion, drawing, and pressing. Perspectives of utilizing the phenomenon to produce even very complex elements in the forming processes by pressure or by using negative pressure, as Jovane showed, appear to be extremely interesting--however under the condition of control of the technical side of the problem for those alloys requiring increased deformation temperature, which (alloys), after all, make up the vast majority. Although up to now the use of superplastic alloys in technology was and is very limited, none the less they awaken a particular interest in the following areas (12):

a. Use of superplastic rolled semi-finished products for drawing and deep pressing, where a substantial reduction in the costs of instrumentation and production is gained. In particular the eutectoid Zn-Al alloy, the most universally recognized as a superplastic material, is considered a competitor of low-carbon steel, since a higher material cost could be entirely compensated by the savings in production costs. With this utilization the absence of the narrowing during deformation is the chief advantage of the superplastic state.

b. Use of the phenomenon as an interim state during mechanical working of complex alloys, where a low yield stress limits working possibilities. The proper hot working used here can produce material having satisfactory high properties.

From among the many tests on the use of the superplasticity phenomenon in technology, undoubtedly the accomplishments of the English industry, based on the Zn-Al alloys with eventual modifications, would have to be placed at the forefront (10, 11, 46).

The well known British firm, Leyland Motor Corporation, jointly with the companies: The Imperial Smelting Corporation, Ltd. and Enfield Rolling Mills mastered the technology of the manufacture of the superplastic zinc-aluminum alloy (ZnAl 22), intended for the manufacture of car bodies and other new industrial applications. The new alloy received the name Prestol (10, 11) and is met in technical literature under this name. Experimental car body parts and other elements made from this alloy would appear to indicate its wide use as a substitute material in the body of vehicles and, above all, there, where the processes of multiple and step pressing are necessary.

Similar tests (46) were conducted on the alloy "ZAM" (Zn 70-82%, Mg 0.08-0.2%, Cu 2%, the rest--Al) under direction of the National Research Development Corporation. In both of the above cited cases the real possibilities of picking up production of the various elements from the above named alloys were confirmed.

It must be remembered, however, that the state of the technological investigations, for the time being, finds itself in the initial stage, and the first positive results obtained so far solely in the cases of extrusion or pressing by air pressure or by using negative pressure cannot be referred to the remaining methods of plastic working, where with respect to the complexity of the conditions of deformation, as well as the matter of maintaining the temperature necessary for the given alloy, great technical difficulties are most likely encountered. There is no doubt that only further systematic investigations, theoretical as well as experimental, will permit a priori definition of the extent to which the possibilities offered by the phenomenon of superplasticity will be able to be used in the traditional methods of the plastic working of metals and alloys. Before picking up any kind of technological tests using for superplastic strain the traditional processes of plastic working such as rolling, pressing, or extrusion, initial investigations must, of course, be conducted, which include solving the construction diffi-

culties connected with the condition of work arrangment in the required temperature range and the mutual dependencies of parameters accompanying the given distortion process. From this side of the problem the investigations abroad find themselves only in the initial stage.

Conclusion

Taking into consideration the intended development and modernization of the country's manufacture of zinc, and particularly of the rolled products and considering the appearance, experimentally confirmed by the Institute of Nonferrous Metals, of the superplasticity phenomenon in zinc-aluminum alloys, as well as technical and economical benefits from using this phenomenon in technological processes, resulting from the investigations abroad, research continues in the scope of establishing parameters of the technological process of the production and further working of semi-finished products from the above named alloys.

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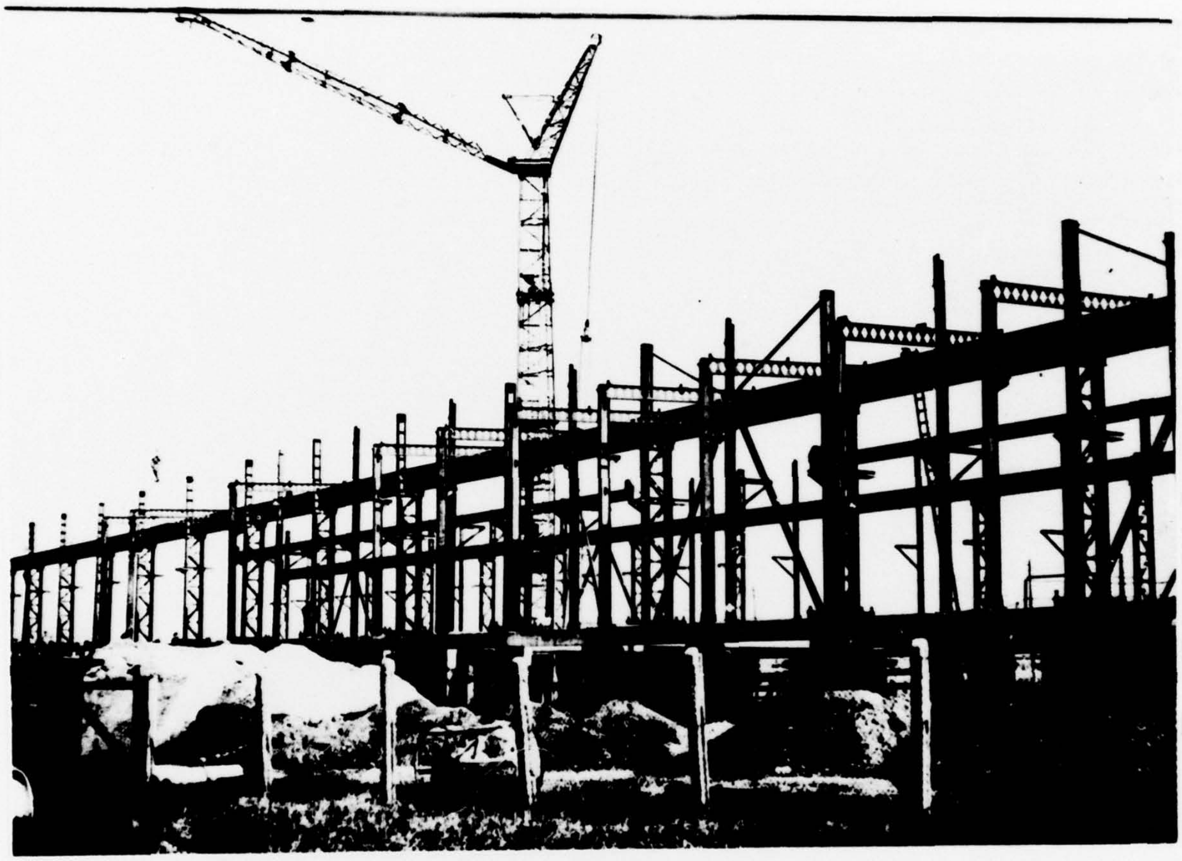

Depot of a rolling mill for grooved copper in Szopienice (under construction). Photo by D. Skotnica.

Fragment of the construction. Photo by D. Suwala.

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C557 USAIIC	1	ETID	3
C591 FSTC	5	NIA/PHS	1
C619 MIA REDSTONE	1	NICD	5
D008 NISC	1		
H300 USAICE (USAREUR)	1		
P005 ERDA	2		
P055 CIA/CRS/ADD/SD	1		
NAVORDSTA (50L)	1		
NAVWPNSCEN (Code 121)	1		
NASA/KSI	1		
544 IES/RDPO	1		
AFIT/LD	1		